Zeta^2 Coronae Borealis, a Spectroscopic Triple System Including an Asynchronous Close Binary

Karl D. Gordon and Christopher L. Mulliss

Ritter Astrophysical Research Center, The University of Toledo Toledo, OH 43606

Electronic mail: karlg@physics.utoledo.edu, cmulliss@physics.utoledo.edu

ABSTRACT

Using the 1-m telescope at Ritter Observatory, we took 36 observations of ζ^2 Coronae Borealis with a fiber-fed échelle spectrograph. From these observations, ζ^2 CrB was found to be a triple system and a new spectroscopic orbit was calculated. This orbit has two periods, a 1.72357 day period for the inner binary composed of ζ^2 CrB A & B and a 251 day period for the outer binary composed of ζ^2 CrB AB & C. The inner binary is a double-lined spectroscopic binary composed of two B7 V stars. The inner binary's center of mass (ζ^2 CrB AB) describes a long-period single-lined variation identified with the outer binary. The inner binary period is significantly shorter than the 12.5842 day period previously calculated by Abhyankar & Sarma (1966). The inner binary possesses an essentially circular orbit ($e = 0.01$) while the outer binary has an eccentric orbit ($e = 0.48$). From the widths of their Si II 6371 Å lines, the $v \sin i$'s were calculated to be 46 ± 7 km s^{-1} for ζ^2 CrB A and 7.5 ± 2 km s^{-1} for ζ^2 CrB B. As ζ^2 CrB A & B have similar masses, their different rotational velocities make this system a sensitive test of synchronization theories.

Subject headings: stars: individual (ζ^2 CrB) – binaries: close – binaries: spectroscopic

1. Introduction

The B7 V star ζ^2 Coronae Borealis (HD 139892, HR 5834, ADS 9737 A; $\alpha(2000) = 15^{\rm h}39^{\rm m}22\overset{\rm s}{.}66$, $\delta(2000) = +36°38'9\overset{''}{.}26$) has been known to be a double-lined spectroscopic binary since the work of Plaskett (1925). ζ^2 CrB is the brighter component ($\Delta m = 1.0$) of the visual double star ADS 9737 with a separation of $6\overset{''}{.}4$ from the fainter component ζ^1 CrB (Hoffleit 1982). Abhyankar & Sarma (1966), hereafter AS66, refining the orbit of Plaskett (1925) found a period of 12.5842 days from 58 observations. They comment on the difficulty of measuring the double broad lines of ζ^2 CrB, which is evident in their observed radial velocities' large deviations from their calculated orbit (see Fig. 1 & 2 of AS66). As a result, their orbit received a 'd' (poor orbit) classification in the *8th Catalogue of the Orbital Elements of Spectroscopic Binary Systems* (Batten et al. 1989).

In an effort to understand the large deviations found by AS66, ζ^2 CrB was added to the observing program at Ritter Observatory. From the first few spectra of ζ^2 CrB, we noted that the lines associated with the two components of ζ^2 CrB (A & B) were broadened by different amounts. As AS66 found the two components of ζ^2 CrB to have nearly identical masses and a relatively short period, ζ^2 CrB is expected to be tidally interacting (Tassoul & Tassoul 1992). This tidal interaction is predicted to synchronize the orbital and rotational periods of the binary. Thus, ζ^2 CrB makes possible a sensitive test of synchronization theory, as the two components have similar masses yet show different rotational velocities.

In §2, we describe the observations. The measurement of the radial velocities, the computation of the $v \sin i$'s, and the determination of the orbital parameters of ζ^2 CrB are detailed in §3. Section 4 contains a discussion of the results.

2. Observations

The observations were carried out between May 1994 and July 1996. The Ritter Observatory 1-m telescope was used in conjunction with an échelle spectrograph connected to the Cassegrain focus of the telescope by a fiber optic cable. The spectrograph camera was fabricated by Wright Instruments Ltd. and utilized a 1200×800 thick chip CCD with 22.5μm square pixels. The CCD was liquid-nitrogen cooled to an operating temperature of 140 K. Data acquisition was controlled by an IBM compatible personal computer running software supplied by Wright Instruments, Ltd.

The reduction of the data was done in the Interactive Data Language (IDL) with a specialized program written for Ritter Observatory spectra (Gordon 1996) based on methods detailed in Hall et al. (1994). A brief outline of the reduction process is as follows. The average bias and flat field were constructed on a pixel-by-pixel basis allowing the removal of cosmic ray hits. The average bias was subtracted from the average flat field, object, and comparison frames. The flat field was used to determine the order and background templates. The background template was used to remove the scattered light from the flat field, objects, and comparisons after fitting a polynomial to the inter-order background on a column by column basis. Cosmic ray hits in the objects and comparisons were removed from consideration by comparison with the average flat field. The normalized, smoothed, flat field profile was squared and multiplied by the object profile, and the resulting function was summed in order to obtain a profile-weighted extraction of the object spectrum. The wavelength calibration was accomplished by scaling all the comparison lines to one super-order and fitting a polynomial to the result, iteratively removing points until a preset standard deviation was achieved. Further information about Ritter Observatory (telescope, instruments, reduction, and archive) can be found on the World Wide Web (WWW) site *http://www.physics.utoledo.edu/www/ritter/ritter.html.*

The observations of ζ^2 CrB are tabulated in Table I, with the UT date, UT time, HJD, and exposure time given in columns 1–4. The spectral coverage consisted of 9 disjoint orders between

TABLE 1

RADIAL VELOCITIES

UT Date [yy/mm/dd]	UT time [hrs:min]	HJD - 2.4×10^6 [days]	exp. time [sec]	ζ^2 CrB A O [km s^{-1}]	ζ^2 CrB A O-C [km s^{-1}]	ζ^2 CrB B O [km s^{-1}]	ζ^2 CrB B O-C [km s^{-1}]
94/05/18	4:60	49490.711	1800	-12.3	-19.3	-21.5	1.1
94/05/19	6:27	49491.772	2700	-98.9	-7.4	87.1	0.8
94/05/20	5:24	49492.728	1200	98.8	3.4	-119.4	1.0
94/05/22	5:11	49494.719	3000	98.2	14.4	-109.3	-1.5
94/05/28	5:12	49500.719	3000	-112.7	-10.3	98.6	1.1
94/05/29	4:31	49501.692	2400	70.7	9.4	-84.7	-0.9
94/06/07	2:37	49510.612	1800	-45.2	10.4	42.1	-1.9
94/06/09	3:33	49512.650	2000	-121.7	-4.7	111.0	-0.7
94/06/10	3:02	49513.629	2400	88.3	-4.1	-120.8	-0.7
94/06/12	2:43	49515.616	2400	8.9	-1.0	-29.0	0.4
94/08/30	1:46	49594.572	3600	80.1	8.1	-157.1	-0.1
94/09/02	1:57	49597.579	3600	-29.3	-6.3	-57.0	1.0
94/09/04	1:31	49599.561	1800	53.8	-2.2	-149.2	0.4
95/03/03	9:34	49779.900	3600	-125.6	-14.1	101.0	-0.4
95/03/15	7:03	49791.796	3600	-115.5	2.6	102.4	-2.0
95/06/20	4:56	49888.708	2700	-55.1	35.5	-1.0	0.3
95/07/01	5:53	49899.747	2700	67.3	6.5	-136.3	-0.3
95/07/02	3:57	49900.666	3600	-97.3	10.9	52.1	-1.1
95/07/03	3:42	49901.656	3600	10.5	6.5	-67.2	1.3
96/03/01	7:55	50143.832	1800	-24.5	47.4	-8.1	2.1
96/03/01	8:32	50143.858	1800	-9.8	52.2	-19.9	1.2
96/03/01	9:06	50143.881	1800	-22.8	30.2	-28.3	2.5
96/03/01	9:40	50143.905	1800	-3.6	40.1	-43.3	-2.2
96/04/24	7:15	50197.806	3600	104.9	4.5	-131.0	-0.4
96/05/02	4:32	50205.693	3600	-96.4	-0.3	87.9	-1.1
96/05/14	3:09	50217.635	3600	-100.8	13.2	110.2	-0.5
96/05/20	4:25	50223.687	3600	91.9	-8.9	-126.0	0.2
96/05/20	7:44	50223.826	3600	54.6	-19.9	-97.5	-0.4
96/05/22	6:23	50225.769	3600	-12.1	-6.7	-11.4	-2.8
96/05/30	3:52	50233.664	3600	50.8	8.1	-61.7	-0.2
96/05/31	3:24	50234.645	3600	-110.6	-15.9	89.8	-0.6
96/05/31	7:32	50234.817	3600	-111.6	3.8	114.8	1.5
96/06/03	4:17	50237.682	3600	59.0	5.5	-73.8	-0.2
96/06/21	6:06	50255.756	3600	-55.7	18.4	69.2	3.1
96/06/26	3:20	50260.641	3600	-118.9	-3.1	113.1	1.6
96/07/04	3:47	50268.659	3600	65.2	-1.9	-93.5	-1.3

5200 Å and 6600 Å with each order approximately 70 Å wide. Lines of interest were Hα, He I 5876 Å, and Si II 6347,6371 Å. The slit width of the spectrograph was chosen to give a resolving power of $R \approx 25,000$. With this resolving power, the average signal-to-noise ratio (S/N) of the observations of ζ^2 CrB was about 100. With this high S/N ratio, it was easy to distinguish the two components of ζ^2 CrB (narrow versus broad) by examining the composite Si II 6371 Å line. As the Si II 6371 Å line is a weak line in B7 V stars, it was important to get high S/N observations.

3. Analysis

3.1. Radial Velocities

The radial velocities were determined two ways, by fitting Gaussians to individual lines and by cross-correlating the weak Si II 6371 Å line. The lines fit to Gaussians were Hα, Si II 6347, 6371 Å, and He I 5876 Å. The results for each line were averaged together after the rest wavelengths of Hα and He I 5876 Å were shifted until their radial velocities roughly matched the Si II radial velocities. This was done as both Hα and He I 5876 Å are multiplets with their rest wavelengths dependent on the different strengths of the individual lines in the multiplet.

The resulting average radial velocities determined from fitting Gaussians were used in constructing templates for the cross-correlation method. The templates were constructed in a manner similar to Cardelli & Ebbets (1993). Each observed spectrum was assumed to include four sources - ζ^2 CrB A (broad lines), ζ^2 CrB B (narrow lines), ζ^1 CrB, and atmospheric lines. On nights with poor seeing, ζ^1 CrB contributed to the spectrum due to the large size of the fiber ($d = 5''$). Atmospheric lines were present in most of the spectra with strengths dependent on the water content of the atmosphere. A template was constructed for ζ^2 CrB A, ζ^2 CrB B, the average ζ^1 CrB spectrum, and an average atmospheric spectrum. Each template was constructed by iteratively dividing each spectrum by the other three templates and then coadding all the spectra in the rest frame of the template. The spectra used in constructing the templates were those in which the broad and narrow lines were separated by over 100 km s^{-1}. After 10 iterations, no significant change in the templates was seen. These templates were used to cross-correlate the individual spectra and determine radial velocities used in the rest of this paper.

Table 1 lists the radial velocities determined from cross-correlating the spectra with the ζ^2 CrB A & B templates. Columns 5 & 7 of Table 1 list the radial velocities for ζ^2 CrB A & B, respectively. The cross-correlation worked well for the narrow lines of ζ^2 CrB B, but for the broad lines of ζ^2 CrB A it was difficult choosing the right peak in the cross-correlation spectrum. As a result, the error in ζ^2 CrB A's radial velocity measurements was ≈ 10 km s^{-1} and the error for ζ^2 CrB B's radial velocities was ≈ 1.5 km s^{-1} (see §3.3). While the narrow line was not affected by pair blending in spectra when the two lines were separated by less than 50 km s^{-1}, the broad line was affected. For these spectra the radial velocities measured by either method for the broad line were systematically too close to the velocity of the narrow line.

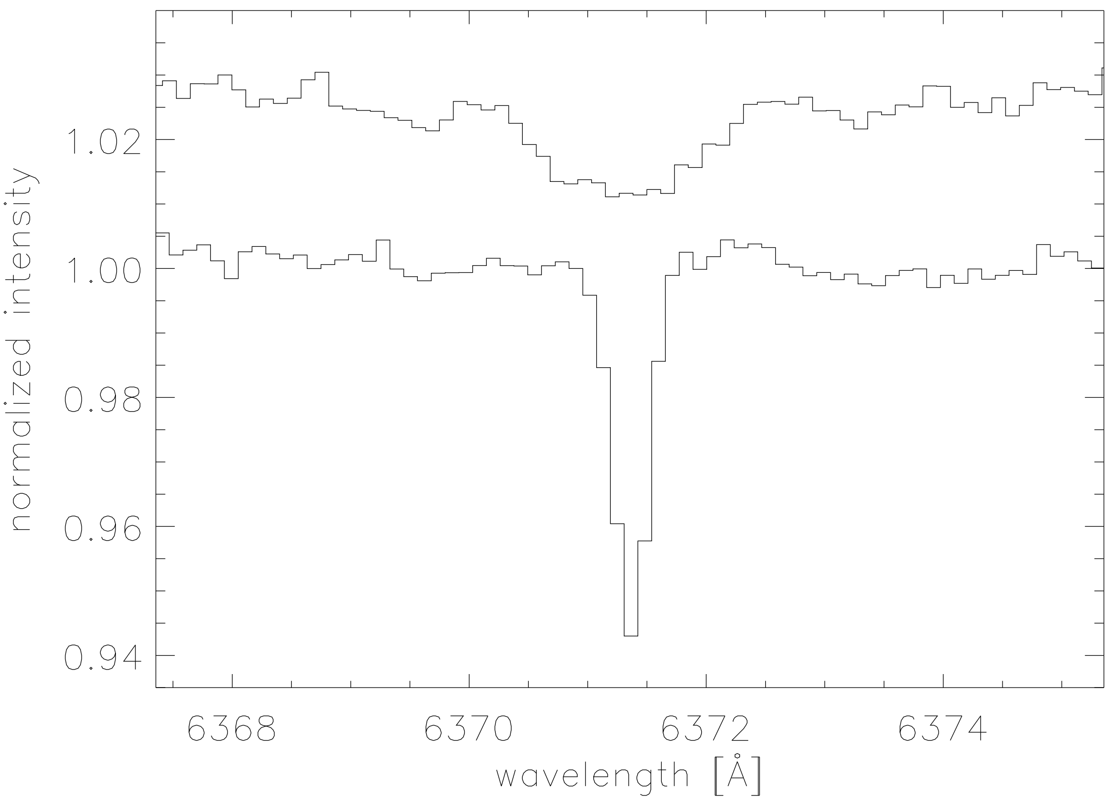

Fig. 1.— The Si II 6371 Å line in the templates for ζ^2 CrB A (top) and ζ^2 CrB B (bottom) is plotted. Note the difference between the rotational broadenings of the line for ζ^2 CrB A & B.

3.2. $V \sin i$

As the templates were constructed from many individual spectra, they had a S/N greater than 500, a large improvement over the individual spectra. The region around the Si II 6371 Å line in both templates of ζ^2 CrB A & B is plotted in Fig. 1. As can be seen from Fig. 1, the line in ζ^2 CrB A's spectrum has the elliptical shape expected from fairly fast rotation, while the line in ζ^2 CrB B's spectrum has a Gaussian shape expected from fairly slow rotation. Using the templates, the half width at half maximum (HWHM) was measured as 37 ± 2 km s^{-1} for ζ^2 CrB A and 8 ± 1 km s^{-1} for ζ^2 CrB B. These measured HWHM were instrumentally debroadened using an instrumental HWHM of 5.5 km s^{-1} resulting in HWHM of 36 ± 2 km s^{-1} and 6 ± 1 km s^{-1} for ζ^2 CrB A & B, respectively. The $v \sin i$ values were computed using the standard half-width method in which the unbroadened line is assumed to be arbitrarily sharp but with a finite equivalent width (Collins & Cranmer 1991). The value of the limb-darkening coefficient, α, can vary between 0.0 and 1.0 with the standard value being 0.6. The values of $v \sin i$ corresponding to $\alpha = 0.0$, 0.6, & 1.0 were 41.7, 49.2, & 51.0 km s^{-1} for ζ^2 CrB A and 6.7, 7.9, & 8.2 km s^{-1} for ζ^2 CrB B. Using the standard method for computing $v \sin i$ has been shown to be accurate to the 10% level for slowly to moderately rotating (< 125 km s^{-1}) early-type stars (Collins & Truax 1995). Taking into account the error in the half width and the range of possible values of α, the values of $v \sin i$ were 46 ± 7 km s^{-1} for ζ^2 CrB A and 7.5 ± 2 km s^{-1} for ζ^2 CrB B.

3.3. Orbit

Due to the difficulty in measuring the radial velocities of broad lines of ζ^2 CrB A, all but one of the orbital parameters for ζ^2 CrB were determined from the radial velocities of ζ^2 CrB B. The K amplitude of ζ^2 CrB A was determined by assuming the ζ^2 CrB B's orbital fit and only fitting the K amplitude of the radial velocities of ζ^2 CrB A. Orbital fits were done using the IDL procedure CURVEFIT which was taken from Bevington (1969). A more specific program for computing spectroscopic orbits by Wolfe, Horak, & Storer (1967) was also run producing similar results.

Using all of ζ^2 CrB B's radial velocities resulted in an orbit with a period of 1.72 days, over a factor of 7 smaller than the orbital period calculated by AS66. The residuals calculated from the 1.72 day orbit were as large as 20 km s^{-1}, much higher than could be attributed to measurement errors. From measurements of standard radial velocity stars taken on the same nights as the ζ^2 CrB observations, the radial velocity error for a narrow line was about 0.2 km s^{-1}. These large residuals could only be a result of another period in the radial velocities of ζ^2 CrB B.

As B7 V stars are unlikely to have pulsations (Waelkens 1991, Sterken & Jerzykiewicz 1993), a third star in ζ^2 CrB was the most likely cause of the residuals. In order to possess a stable orbit, the third star would need to have a significantly longer period than the inner binary consisting of ζ^2 CrB A & B. Therefore, an orbit for the inner binary was fitted to observations closely spaced in

time. There were two such data sets, HJD = 2449490.711 to 2449515.616 and HJD = 2450197.806 to 2450268.659. The orbits fitted to these two data sets had residuals on order of 1 km s^{-1}, a great improvement over the previous fit using all the data. The orbits determined from the two data sets were essentially the same, except for a 1 km s^{-1} shift of their systemic velocities, which was within the systemic velocity errors. Combining both data sets resulted in an improved fit. An orbit for ζ^2 CrB A was found by adopting all the orbital parameters from ζ^2 CrB B's fit, except for the K amplitude which was fit using ζ^2 CrB A's radial velocities.

The residuals computed from observations where both ζ^2 CrB A & B's radial velocities were at least 30 km s^{-1} from the systemic velocity were found to be correlated with a linear correlation coefficient of 0.65. Bevington (1969) gives a 0.1% probability that such a correlation coefficient involving 26 points would arise randomly. Thus, the residuals of ζ^2 CrB A & B have the same origin and this provides concrete evidence that ζ^2 CrB is actually a triple system.

The outer binary, assumed to consist of the inner binary (ζ^2 CrB A & B) and an unseen third star (ζ^2 CrB C), was examined by looking at the residuals of ζ^2 CrB B's orbit. As the residuals of ζ^2 CrB A & B were correlated, changes in ζ^2 CrB B's residuals were the result of ζ^2 CrB C's orbit around ζ^2 CrB A & B. The phase coverage was sufficient to derive an orbit, but this orbit was not well determined due to the lack of observations between phases 0.95 and 1.05. The orbital fits to both ζ^2 CrB B and ζ^2 CrB AB were refined iteratively by subtracting the contribution from one orbitial fit from ζ^2 CrB B's radial velocities, fitting for the other orbit, and repeating. After the fifth iteration little change was seen in the fitted orbital parameters. The final orbital parameters for both the inner binary and the outer binary are tabulated in Table 2. Columns 6 & 8 in Table 1 give the residuals (O-C) after subtracting both inner and outer binary orbits. These residuals were used to estimate the errors in an individual radial velocity measurement giving 10.5 km s^{-1} for ζ^2 CrB A and 1.2 km s^{-1} for ζ^2 CrB B. Figures 2 & 3 plot the fitted orbits and radial velocities for both the inner and outer binaries, respectively. The orbital fits for the outer and inner orbits have been removed from the radial velocities plotted in Figures 2 & 3, respectively.

3.4. Inclination

In non-eclipsing, unresolved binaries a common method to determine the inclination is to assume one of the stars is synchronously rotating. This assumption implies the rotational and orbital periods are equal and the rotational and orbital axes are parallel. The equatorial velocity of the star is computed from an assumed stellar radius and then the inclination is computed from the star's measured $v \sin i$.

For ζ^2 CrB, we applied this method assuming ζ^2 CrB A (broad lines) was synchronously rotating. Assuming ζ^2 CrB B (narrow lines) synchronously rotates resulted in a equatorial velocity for ζ^2 CrB A larger than its breakup velocity. The radius was assumed to be 2.38 $R_\odot$, but is only accurate to 50% (Andersen 1991). Using this radius and the range in $v \sin i$ calculated in §3.2,

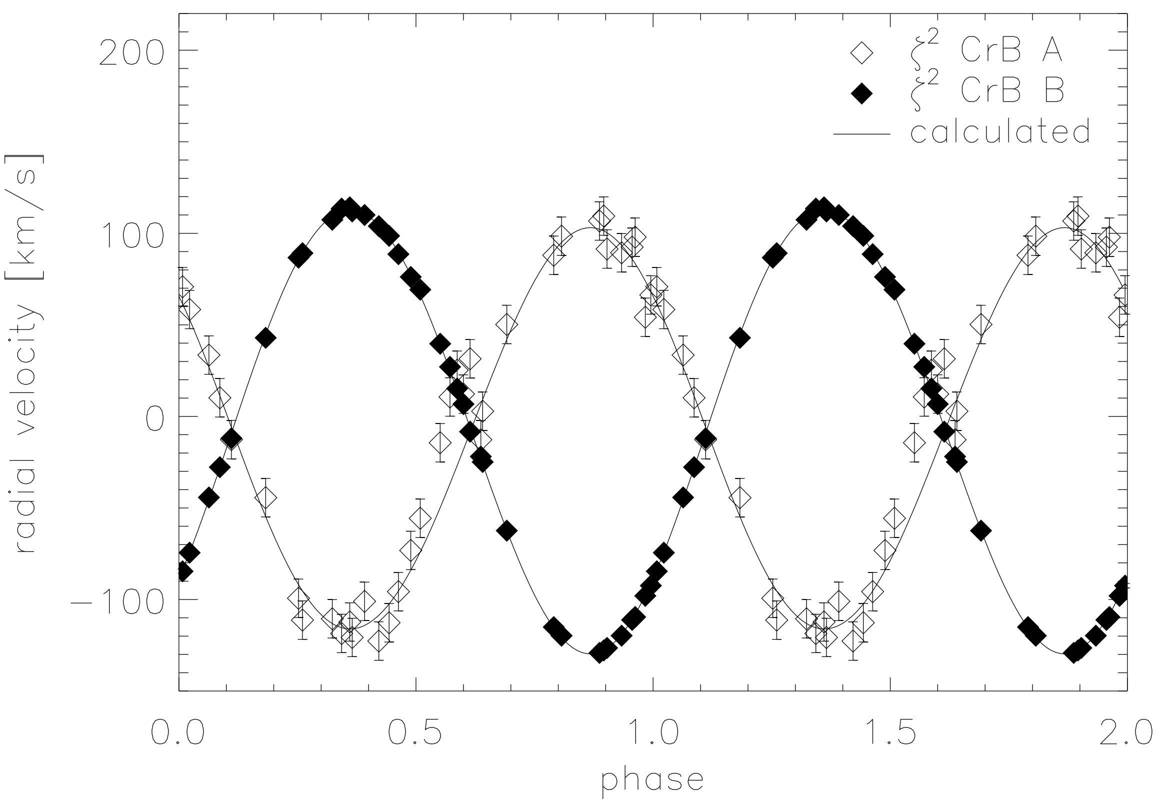

Fig. 2.— The radial velocities for both ζ^2 CrB A & B are plotted phased to the inner binary period, 1.72 days, given in Table 2. The fitted orbit to the outer binary has been subtracted from the radial velocities plotted. The solid lines are the fitted orbits using the parameters listed in Table 2. Note the large errors in the radial velocities of ζ^2 CrB A when it is near the systemic velocity of the system.

TABLE 2
Orbit Parameters

	ζ^2 CrB A	ζ^2 CrB B	ζ^2 CrB AB
V_o	-21.9 ± 0.4 km s^{-1}		
P [days]	1.72357 ± 0.0001		251.5 ± 0.6
T [days]	2450196.2793 ± 0.0137		2449373.5 ± 1.7
e	0.013 ± 0.002		0.48 ± 0.03
K [km s^{-1}]	109.6 ± 13.6	121.2 ± 0.3	28.5 ± 2.0
ω	$49^\circ \pm 3^\circ$	$229^\circ \pm 3^\circ$	$191\overset{\circ}{.}8 \pm 2\overset{\circ}{.}9$
$a \sin i$ [R$_\odot$]	3.73 ± 0.46	4.13 ± 0.01	124 ± 7
$m \sin^3 i$ [M$_\odot$]	1.155 ± 0.142	1.045 ± 0.142	$\cdots$

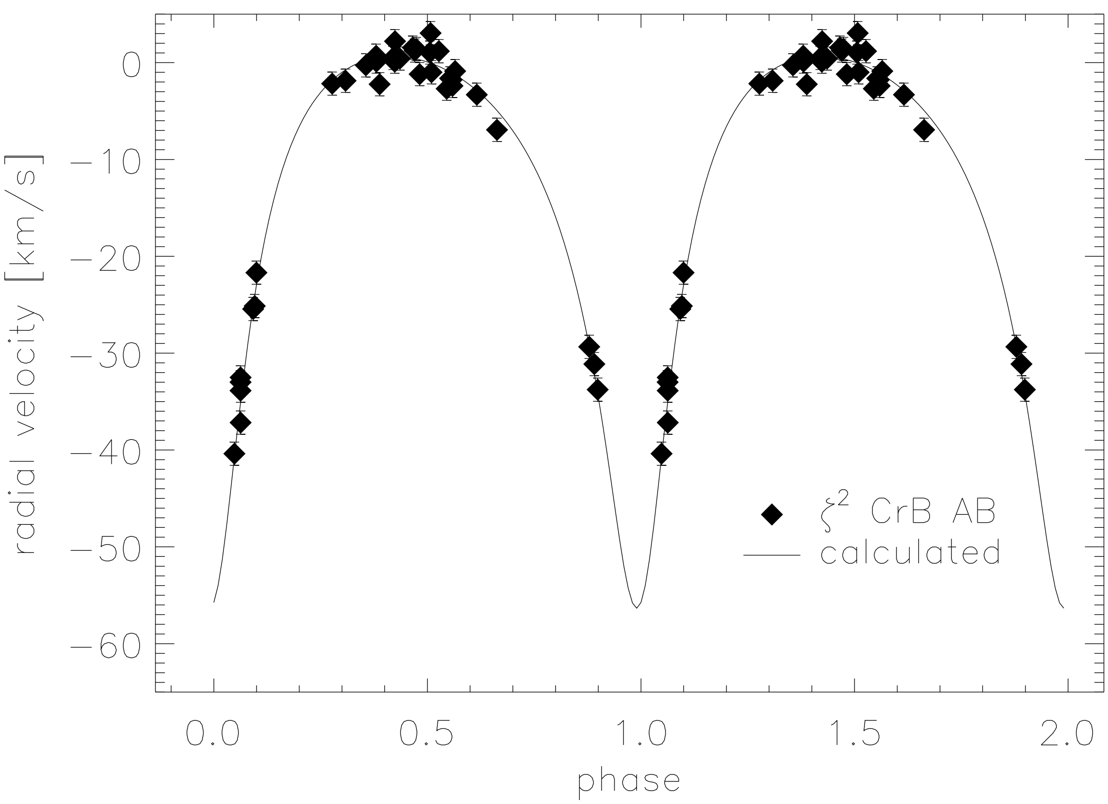

Fig. 3.— The radial velocities for ζ^2 CrB B are plotted phased to the outer binary period, 251.5 days, given in Table 2. The fitted orbit to the inner binary has been subtracted from the radial velocities plotted. The solid line is the fitted orbit using the parameters listed in Table 2.

the resulting range in $\sin i$ was 0.62–0.76. Using these values of $\sin i$, the range in masses was 4.83–2.64 $M_\odot$ for ζ^2 CrB A and 4.37–2.39 $M_\odot$ for ζ^2 CrB B. For a B7 V star, Andersen (1991) gives a mass of 4.13 $M_\odot$ with an accuracy of 15%. Thus, consistent values for ζ^2 CrB A & B radii and masses were possible if the limb-darkening coefficient, α, is fairly low. Assuming an α of 0.0, gives $i = 38°$.

The mass function for the outer binary (ζ^2 CrB AB & C) was computed to have a value of 0.42 ± 0.11 $M_\odot$. Assuming that all three components of ζ^2 CrB are coplanar and have the range in $\sin i$ calculated above, the mass function can be solved for ζ^2 CrB C's mass. The mass range for ζ^2 CrB C was computed to be 8.5–3.5 $M_\odot$. Such a massive star would be visible in the spectrum of ζ^2 CrB. Due to the lack of observations between the critical phases 0.95 and 1.05 of the outer binary orbit, the fitted K amplitude is likely to be too large. Reducing the K amplitude by a few km s^{-1} would greatly reduce ζ^2 CrB C's mass as the mass function is proportional to K^3.

4. Discussion

The significant results of this work were the discovery that ζ^2 CrB is a triple system, the inner binary has a much shorter period than previously thought (AS66), and ζ^2 CrB B is rotating asynchronously.

The identification of ζ^2 CrB as a triple system and the 1.72357 day inner binary period most likely explains the large residuals of AS66's orbit. AS66 calculated such a different period, 12.5842 days, most likely for two reasons. First, they only calculated corrections to Plaskett's (1925) orbit. Second, they only measured H and He lines which, as multiplets, are intrinsically broadened. As a result, the H and He lines appear to have similar widths making an identification of broad versus narrow difficult. Only with high S/N spectra and a weak, intrinsically narrow line, such as Si II 6371 Å, were we able to distinguish consistently between lines from ζ^2 CrB A & B. In fact, AS66's data are consistent with our fitted orbits with only a small number of their points having wrong identifications.

Using AS66's orbit, the lower limit on the masses of ζ^2 CrB A & B ($m \sin^3 i$) were 9.9 $M_\odot$ and 9.4 $M_\odot$, respectively. AS66's lower limits on the masses are over a factor of two greater normal mass of a B7 V star which is 4.13 $M_\odot$ (Andersen 1991). Using our orbit, the lower limit on the masses of ζ^2 CrB A & B are 1.155 ± 0.142 $M_\odot$ and 1.045 ± 0.142 $M_\odot$, respectively. These lower limits are consistent with the mass of a B7 V star clearing up the contradiction implied by AS66's work.

The two components of the inner binary, ζ^2 CrB A & B, have equal masses within the error bars, yet possess very different rotational velocities. From the work of Tassoul & Tassoul (1992) and Claret et al. (1995), the circularization and synchronization time-scales were computed to be 10^6–10^7 and 10^4 years, respectively. From the above calculations, ζ^2 CrB B should have synchronized its rotation even before the inner binary circularized. Obviously, some other process

is keeping ζ^2 CrB B from synchronizing. Claret & Giménez (1995) were able to explain the asynchronous rotation in TZ For as due to evolutionary effects. Similarly, evolutionary effects probably explain the asynchronous rotation of ζ^2 CrB B.

More observations of ζ^2 CrB are needed, especially between phases 0.95 and 1.05 of the outer binary. These observations would greatly refine outer binary orbit, specifically its K amplitude and eccentricity.

This work was possible only with the help of the Ritter technician Bob Burmeister and the crack Ritter observing team. Team members contributing observations to this effort were Jason Aufdenberg, Michelle Beaver, Bruce Cantor, David Knauth, Alex Mak, Nancy Morrison, Jens Petersohn, and both authors. We are also thankful for many helpful conversations with Nancy Morrison and Bernard Bopp. Support for observational research at Ritter Observatory is provided by NSF grant AST-9024802 to B. W. Bopp and by The University of Toledo. This research has made use of the Simbad database, operated at CDS, Strasbourg, France.

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